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INVESTIGATING HVAC THERMAL COMFORT AND ENERGY EFFICIENCY IN COMMERCIAL BUILDINGS

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ABSTRACT

HVAC is one of the largest consumers of electrical energy in residential and commercial buildings. Reducing of consumption of energy without compromising thermal comfort may have environmental and financial benefits. Thermal comfort expresses satisfaction with the thermal environment is one of the parameters necessary in building style that in depth modeling and standardization exist. in commercial buildings if thermal comfort is not satisfactory that may effect on human life, which may cause problematic behavior that forms a heavy burden for skilled and informal careers day and night. The main energy consumption contribution within the operation section of contemporary buildings is from their HVAC systems. Tactically HVAC systems could offer healthy and comfortable indoor surroundings, whereas poor design could result in wastage of energy. Historically the look of the systems relies on a continuing range of occupants whereas the situational awareness of the system has been unnoticed. This paper focuses on the investigating of the HVAC system in terms of its information of the occupants of the power in real time. Thermal comfort analysis is applied to check the indoor climate of buildings for economical use of such HVAC systems. Computational Fluid Dynamics (CFD) is used to model and simulate the indoor conditions. Pro-E software used for Building information Modeling (BIM) to be a platform to integrate all the information of commercial building standards, and using of CFD software check the inside thermal comfort levels and energy distribution at inside the room.

KEYWORD: Head: HVAC, Thermal Comfort, CFD, BIM & Energy Distribution

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Original Article

INTRODUCTION

About 90% life of an average individual is spent in the indoor environment (US, EPA, 2015). A major portion (40%) of the world's energy is consumed in buildings; indoor thermal comfort accounts for 30-40% of that energy (European Union, 2015). The available sources of energy are becoming expensive, insecure and producing pollution therefore energy efficiency will play an ever-increasing role in ensuring sustainable energy use (EIA, 2014; Lombard, 2008). Therefore, well-designed building ventilation systems must be installed to optimize the use of energy while providing satisfaction to the building occupants (Redlich, et al., 1997). Thermal comfort is an important aspect in representing human satisfaction, which is defined as "the condition of mind which expresses satisfaction with the thermal environment (ASHRAE, 2004; ISO 7730, 2005)". A wide range of research has been carried out on residential and non-residential thermal comfort level. For instance, thermal comfort in 22 air-conditioned office buildings in different climates have been analyzed by Cena and Dear (1999), in which a relationship was observed between job satisfaction and thermal comfort level. In US, Canada and Finland, 61 % of occupants were found not to be satisfied with the adjusted temperature in their office according to survey conducted in 215 building (Huizenga et al., 2006). Thermal comfort analysis is one of the most useful methods of

identifying thermal perceptions of occupants in a particular building space and of possible energy savings. Studies showed that the internal climate of a room is the strongest factor in maintaining thermal comfort. Direct manipulation of the internal climate is necessary to retain an acceptable level of thermal comfort (Nicol et. al, 2002). Accurate modeling of the internal climate of buildings is essential if Building Energy Management Systems (BEMS) are to efficiently maintain adequate thermal comfort (Mullen et. al, 2015). Fanger (1970) introduced a thermal comfort model based on six parameters that are determined by analyzing the whole body satisfaction and local discomfort. The Fanger equation depends on the physiological and environmental parameters such as air temperature, air relative humidity, air velocity, Mean radiant temperature, clothing thermal factor and activity level. Traditionally the design of the HVAC systems is based on a constant number of occupants while the situational awareness of the system has been ignored. However, by automatically control the HVAC according to the number and the location of occupants' may greatly reduce energy consumption in the life cycle of the building. The present research proposes a method to apply thermal comfort analysis based on the locations of HVAC system and the occupants location information collected in real time, so that an automated control of the HVAC system can be applied to save energy. Building Information Modeling (BIM) is acted as a platform to integrate real-time data and the spatial information of the built environment. BIM is a new approach to design, construction, and facilities management in which a digital representation of the building process is used to facilitate the exchange and interoperability of information in a digital format (Eastman and Eastman, 2008). Kryegiel and Nies (2008) indicated that BIM can be applied in sustainability analysis widely while considering for example building orientation, building envelope, and construction materials. Recent research in the building construction industry reveals that Building Information Modeling (BIM) has not been popularly used to take the advantages of the new technology due to several reasons. Lack of knowledge and personnel that familiar with the technology are the major issues. With the introduction of BIM, different attributes of the building envelopes can be recorded in the digital database, for instance carbon dioxide emission, which facilitates the automatic sustainability assessments of buildings. Chen and Hsieh (2013) developed a BIM-assisted rule-based approach to automatically check of greenhouse gas emission of buildings. The normal carbon dioxide emission was calculated from the building and the area of green plants; and then the result would be checked with relevant rules. However, most of these applications are limited to the design stage. The present paper is a part of a research focusing on life cycle evaluation of building sustainability using BIM, RTLS, and integrating LEED standard into the system. Related research results can be found in Zhang et. al, 2013; Zhang et. al, 2014 and Zhang and Chen, 2015. The present paper proposes a methodology by simulating the wind velocity, distribution of air flow in a room using CFD, based on what thermal comfort is analyzed, the HVAC system is smartly controlled according to occupants' number and location. In this way, energy can be used efficiently and waste can be reduced. 2. Computational Fluid Dynamics (CFD) method Since 1950s Computational Fluid Dynamics (CFD) has been extensively used as a scientific tool in many applications and research projects. In 1974, Nielsen presented one of the earliest works where the airflow in rooms was simulated through CFD but due to limited computational resources CFD had to wait. The increase in computational resources has revitalized the use of CFD as a scientific tool and its usage continues to increase. Analysis of fluid flows is done through numerical algorithm in CFD which allows it to model and evaluate the indoor and outdoor airflow, heat transfer and contaminant transport. Therefore, CFD is a powerful tool to analyze thermal comfort and dissatisfied percentage in buildings. A surgery room in a hospital based on the CFD 3D model was analyzed for thermal comfort by Ho et al. (2009), which resulted in the identification of inefficient location of grilles of supply air. The impact of radiant cooling ceiling and mechanical ventilation systems on the thermal comfort using CFD modeling has been evaluated by

Wei-Hwa et al. (2012), based on their results they provided a design guideline for installing a cooling ceiling system in terms of higher satisfaction of occupants. Evaluation of the thermal comfort level with the calibrated and non-calibrated CFD models has been done by Hajdukiewicz et al. (2013), which discussed about the calibrated CFD model in a highly-glazed meeting room with natural ventilation. The casual relationship between health symptoms and pollutant exposures in schools by collecting some parameters such as CO2 concentrations, ventilation rates and so on was evaluated by Daisey et al. (2003), indicating the poor ventilation implemented in many classrooms. CFD compounded computer sciences, numerical techniques and physical sciences. CFD employs a series of finite discrete points to evaluate the original and continuous physical quantity field in space and time by adopting and a set of variable data. A field variable approximation is done by solving the algebraic equation set. Fluent, Airpak and Phoenics are the different platforms for performing for different applications. In this research, Airpak has been selected due to its capacity to model temperature, air velocity, Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD).

LEED EMBEDDED MODEL IN PRO_E SOFTWARE

A Pro-E model is created for the building to integrate energy consumption data with spatial areas, such as rooms. From the heat load calculations (published in previous research paper) requirements from the Leadership in Energy and Environmental Design (LEED) are built into the Pro-E software. Credits obtained from the design and the operation stage will be calculated and the performance of the building will be checked in terms of sustainability. Figure1 shows the plug-in developed in a Pro-E software to integrate LEED requirements. More details can be found in Zhang et al, 2014 and Zhang and Chen, 2015

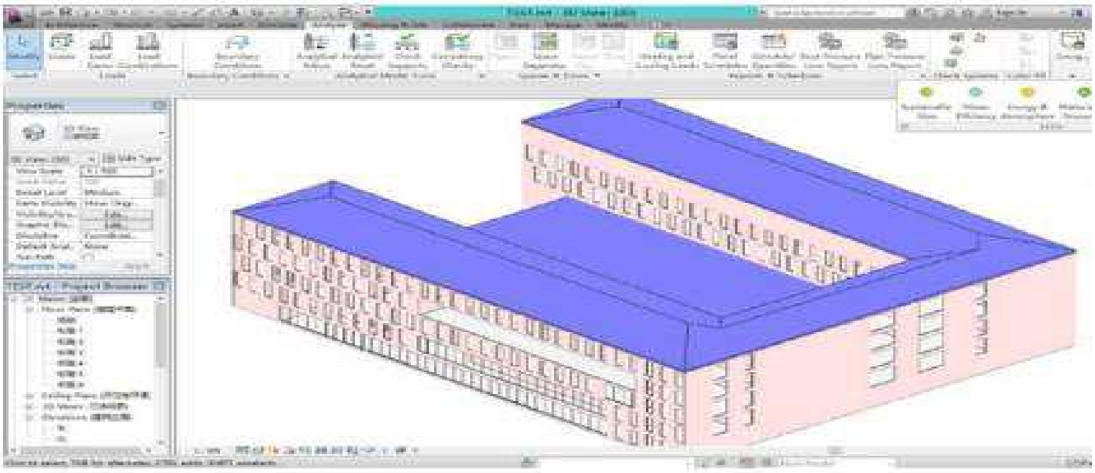


Figure 1: LEED Embedded Pro-E Model

In the present paper, the main focus is the Energy and Atmosphere, Credit 1: Optimize Energy Performance. Integrating the results derived from the CFD modeling into this Pro-E model enables the analysis of the building in terms of comfort and energy consumption. In this way an efficient and effective way to optimize energy consumption is presented which is based on the allocation of people's places according to the requirement of lightning, air conditioning and other related systems. Data of energy consumption collected from the system after applying the automatic HVAC control will be evaluated and improvement will be calculated.

CFD SIMULATION IN THE PRESENT RESEARCH

In this paper, we analyze a commercial building, the performance of air conditioning system and the level of thermal comfort for occupants. Wind velocity and temperature have been simulated by using the CFD method. The Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfied (PPD) are evaluated as well.

Physical Model of the Office

The physical model of the selected office is equipped with two central air conditions installed on the ceiling, as shown in Figure 2.

The Parameters of Model Are As Follows

- Reference coordinate system: start point coordinates (0, 0, and 0) and ending points (8.5, 3, and 10.4);
- Room dimensions: $8.5 \times 10.4\ m$;
- Indoor heating source: 7 sitting men (persons 1 to 7 with calorific value of 75 w; two sitting women (person 8 and 9) with calorific value of 60 w, nine LCDs with calorific value of 19.5 w; nine computer cases with calorific value of 220 w; and finally, nine florescent lamp sets with total power of 100 w for each set which are replaced by 0.4 $m \times 1.2\ m$ blocks;
- Three external windows facing south with geometrical dimensions: $1.6m \times 3m$;
- Two ceiling HVAC air supply outlets: Dimensions: 0.9 × 0.9; air velocity: 2.5 m/s; air temperature:18 ℃; and
- Office door geometry dimensions: $2m$ × 1.3m, However, to simplify the calculation, the door is ignored in the simulation.

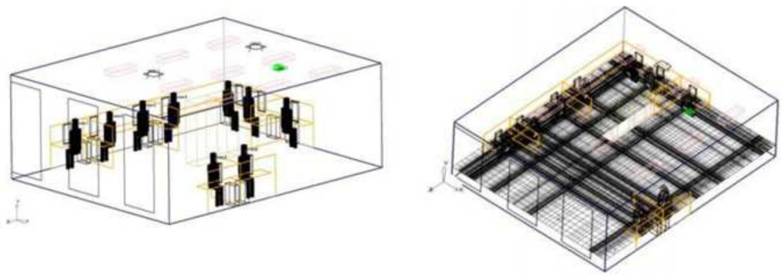


Figure 2: The Geometry of Office With Nine Occupants

Setting of Boundary Conditions

The temperature buoyancy condition for the CFD simulation was provided by Arduino sensors. Indoor and outdoor temperatures are gathered by two DHT11 Arduino temperature and humidity sensors as well. The data for the CFD model were collected during the field measurement in the office on June 15th, 2015 as follows:

- The air was considered as an ideal gas with the reference buoyancy density of 1.173 kg /$m3$;
- (2) Outdoor measured parameters: Dry-bulb temperature at 32 ℃;
- Indoor measured parameters: Dry-bulb temperature at 20 ℃, relative humidity of 40%;

- The only external wall for this office is the south wall, with a constant heat flux boundary condition and 16.8 $W/m2$ considered for heat transfer density;
- Outside windows: placed on the external wall with the heat transfer density of 16.8 $/m2$;
- Internal walls and floor: Front wall (south) with 21.8 ℃, Left wall with 21 ℃, Right wall with 20.2℃ and back wall with 20.4 ℃, floor with 19 ℃ and ceiling with 20.2 ℃;
- Air outlet: Air supply direction is along the Y axis with the dimension of 0.3 m × 0.3 m.The supply air velocity is 2.5 m/s and supply air temperature has an ambient value

Mathematical Model

The grid generation of the model is shown in Figure 2. To calculate the momentum conservation, mass conservation and energy conservation equations, low Reynolds number turbulence model (RNG k-ε model) is implemented. Simultaneously, the influence of heat radiation of each heat source is also considered. In addition, five assumptions are taken into consideration for the physical model. First, Indoor air flow is steady turbulent flow. Second, to conform the Boussinesq theory (1872), which says the buoyancy lift only influenced while changing the fluid density, the indoor air is chosen to be as incompressible. Next, the temperature of floor surface is well-distributed. Fourth, it is assumed good air tightness in the room. Hence, the leakage effect is not considered in the simulated room. Finally, the doors of the office are ignored from the calculation and all windows are assumed to be closed for simplification purpose. The modified mesh for simulation is set as the normal type and the coordinates of X, Y and Z were adjusted to 0.21, 0.1 and 0.07m, respectively.

Intelligent Control System

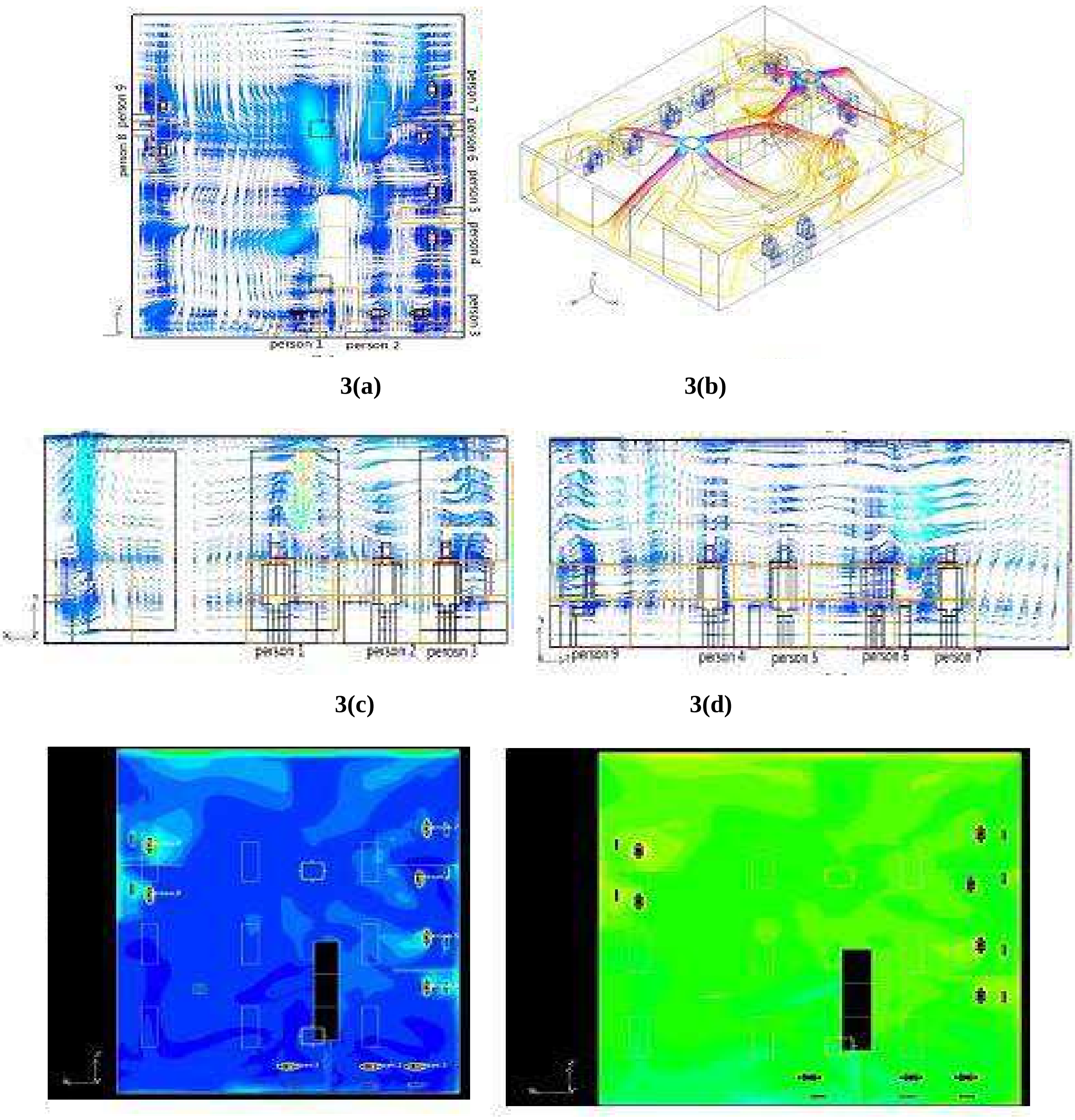
The basic idea of this research is to provide thermal comfort and energy conservation by intelligently controlling the two HVAC air outlets installed in the ceiling of the office. The intelligence is based on its awareness of the occupants' presence in the room and their location so as to decide which of the HVAC system should be kept on or off. The awareness is facilitated by a Real-time Location System based on RFID tags. the locations of users in the building, as can be referred to Zhang et al. (2013). RFID tags are registered in the BIM model and the data written are transferred to the BIM model Properties associated with corresponding tags objects. The decision of which HVAC system should be turn on is taken by the main server at the Facility management office that is connected with a RFID receiver that is present inside the office room and the controller of the HVAC system. The details of this system are beyond the scope of this paper therefore not presented here.

ANALYSIS OF MODEL RESULTS

In order to establish the maximum benefits one common and two extreme scenarios (with respect to the number and location of the occupants) are developed. In the first scenario all the occupants are present in the room so it is decided by the server to keep both the HVAC systems on. For the second scenario the four occupants near the HVAC-1 happens to be present so the it is decided to turn on HVAC-1 and similarly in the third scenario five occupants near the HVAC-2 were present so the decision is to turn HVAC-2 on. For the aforementioned scenarios CFD model have been developed which simulated the Wind velocity and air distributions. Further, the Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfied (PPD) are computed using the data acquired from the experimental measurements performed in the building.

Room1

The indoor air distribution of HVAC systems is related to the indoor temperature, energy consumption of air conditioning systems, human thermal comfort and health status. Therefore, it is essential to ensure the rationality of indoor air distribution. The location of the plane for analysis in the CFD model is depicted through the occupant's position. It should be noted that the locations of occupants are separated by partitions in this office. Figure 3 illustrates the simulation of the office room with nine occupants. To analyze the distribution of airflow in this room, the airflow streamlines also are depicted in figure 3(a). The airflow streamlines were entered through the air conditions and exited through the outlet channel. The air from the air conditioning systems injected from four separate channels by the angle of 45 degree.



3(a) **3(b)**

3(c) **3(d)**

3(e) **3(f)**

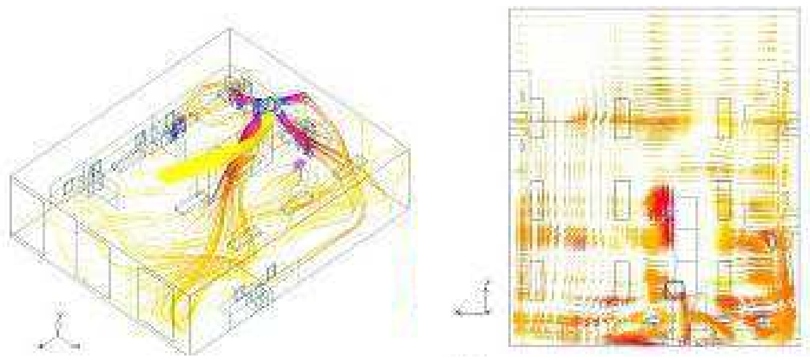
Figure 3: Analysis of the Room1 with Nine Occupants and Two Inlet HVAC Units

Hence, the distribution of airflow, in terms of occupant's location, is well-designed. Moreover, due to the location of air conditioning systems which are placed on the ceiling, there is not any side effect for utilizing the partitions in this

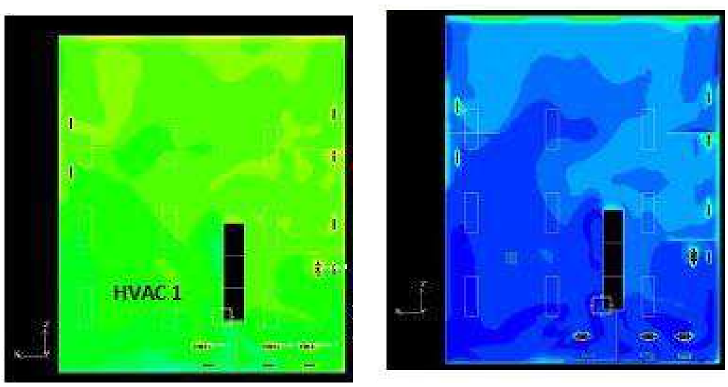
office. Figure 3(b) illustrates the airflow distribution inside the modeled room. The result determines that the air flow inside the room is wind driven. Figure 3(c) depicts a relatively high airflow between occupants 6 and 7 and from the air velocity of figure 3(d), it is concluded that airflow is extremely high for person 1 which again may result in local discomfort for this person. The average air speed in this room in the height of 1.077 meter is less than 0.5 m/s. In terms of the air velocity, there are two high speed airflow areas in the middle of the room. However, no occupants located in this area. Figures 3(e) and 3(f) illustrate the PMV and PPD models, respectively. Both images confirm that locations near windows are not suitable for occupants. Persons 5, 8 and 9 are located in a slightly hot area. Person 9 is located in the 25 percent dissatisfied area. Most of dissatisfied and slightly hot areas are identified near windows.

Room 2

In this room2 only four occupants near the HVAC-1 are presented in the room. The intelligent system can recognize this situation and only turn the HVAC-1 on. Figure 4(a) illustrates the airflow streamlines in this condition. The left-south of the room has less air distribution. The air-velocity is depicted in figure 4(b) which confirms the area near the off HVAC system has lower air flow. In terms of PMV and PPD analysis, figures 4(c) and 4(d) show the south areas in this room is not suitable for sitting occupants in this scenario. However, in terms of energy management, 50% of the energy usage is saved as one of the HVAC systems is turned off by the intelligent system. According to the prepared questionnaire and experimental test based on hourly thermal comfort analysis, it was indicated that only during the first hour, occupants may feel discomfort. However, after the first hour, occupants feel much more comfortable. Hence, one HVAC outlet needs more time to adjust the temperature and prepare a comfort range.



4(a) **4(b)**



4(c) **4(d)**

Figure 4: Analysis of the Room with Four Occupants and HVAC-1

CONCLUSIONS

An intelligent control system is designed to automate the decisions taken to provide thermal comfort in real time depending on the number and location of the occupants. The evaluation of the decisions taken by system in terms of thermal comfort based on wind velocity, distribution of air flow is done through CFD modeling. One common and two extreme scenarios in terms of location and number of occupants are tested. The results reveal up to 50% of energy saving under extreme scenarios and with thermal comfort parameters between acceptable ranges. These results are embedded in a BIM model along with the LEED standards which is capable of rule based automatic evaluation. This will provide an efficient way to assess different scenarios and perform spatial analysis during design to avoid re work and improve green grade as well as enable the manager or the owner to forecast and diagnose energy consumption and achieve energy efficiency. Most importantly give the end users a good awareness about how to properly use the designed features in the building and reduce energy wastage in daily life.

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